LONDON-WEST MIDLANDS ENVIRONMENTAL STATEMENT

Volume 5 | Technical Appendices

CFA11 | Stoke Mandeville and Aylesbury

Stoke Brook modelling report (WR-004-003)

Water resources

November 2013

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1.1 Structure of the water resources and flood risk assessment appendices

1.1.1 The water resources and flood risk assessment appendices comprise four parts. The first of these is a route-wide appendix (Volume 5: Appendix WR-001-000).

1.1.2 Specific appendices for each community forum area (CFA) are also provided. For the Stoke Mandeville and Aylesbury area (CFA11), these are:

- a water resources assessment (Volume 5: Appendix WR-002-011);
- a flood risk assessment (Volume 5: Appendix WR-003-011); and
- a hydraulic modelling reports for the Stoke Brook to the south of Stoke Mandeville (i.e. this Appendix).

1.1.3 Maps referred to throughout the water resources and flood risk assessment appendices are contained in the Volume 5, Water Resources and Flood Risk Assessment Map Book.

1.2 Scope and structure of this assessment

1.2.1 This document presents the hydraulic modelling that was undertaken for the Stoke Brook to the south of Stoke Mandeville. The purpose of the modelling is to supplement the baseline flood risk datasets upstream of the proposed crossing to supplement the flood risk assessment.

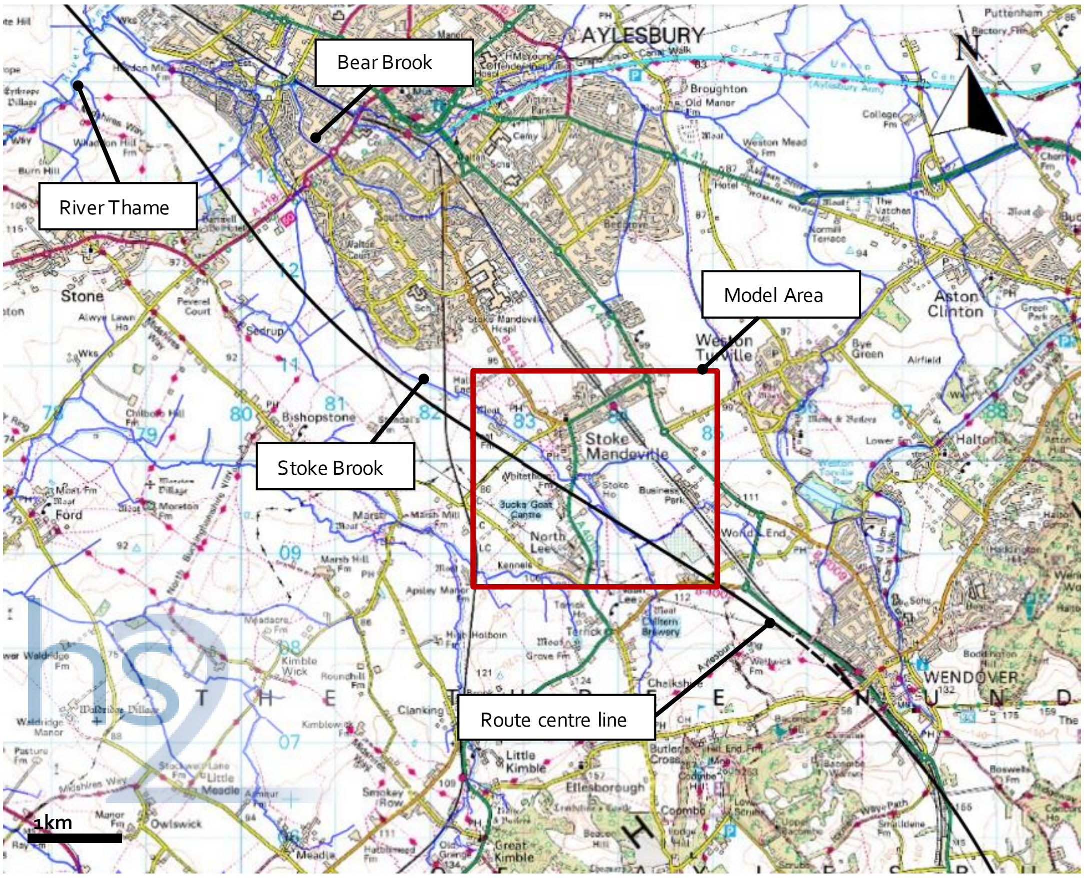
1.2.2 The catchment hydrology is reported in Section 2. Flood water levels, depths and floodplain extents are reported for the baseline in Section 3. Section 4 includes conclusions and recommendations, and Section 5 covers assumptions and limitations of the hydrology and hydraulic modelling.

2 Hydrology

2.1 Location plan and topography

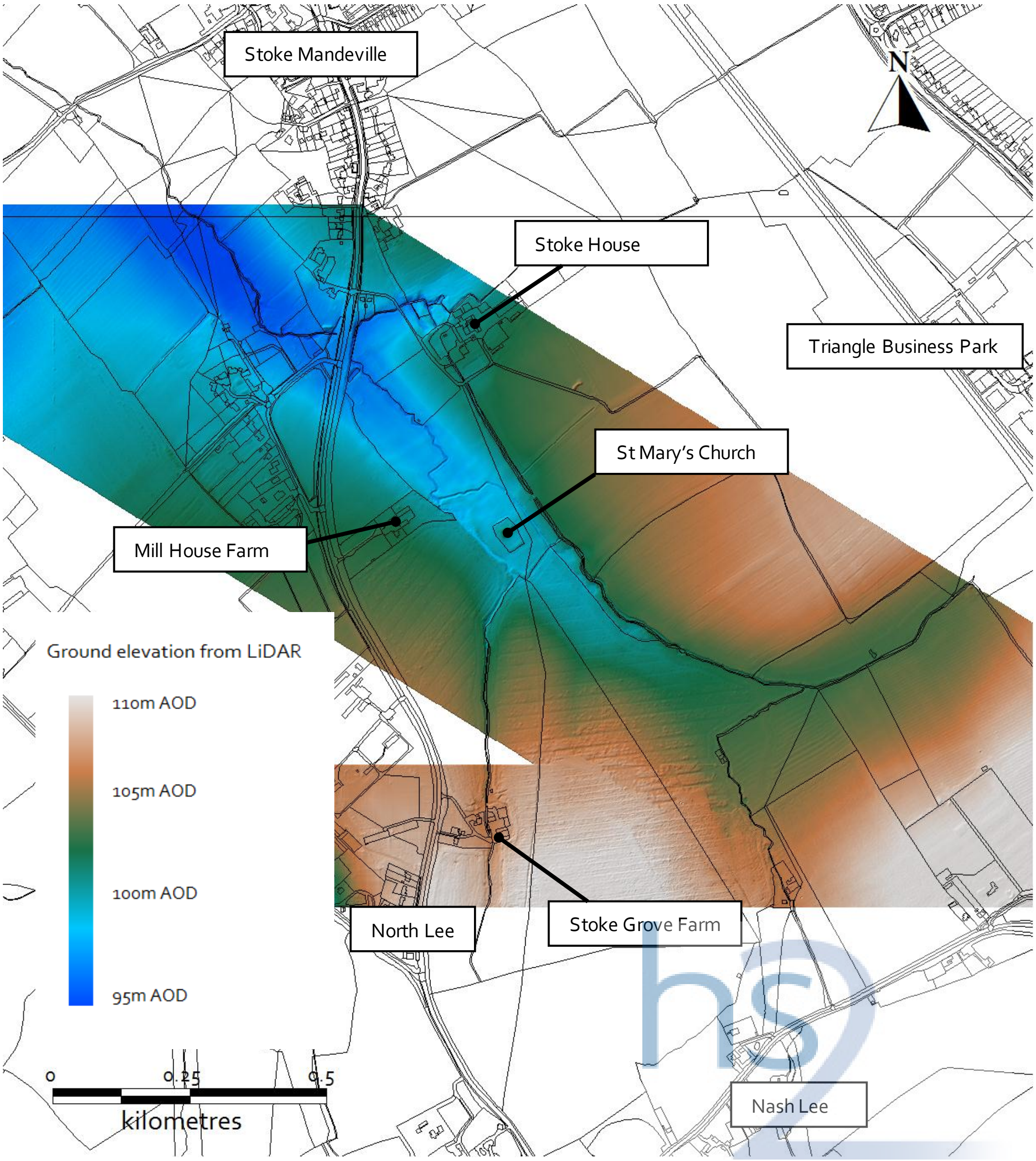
2.1.1 The study catchment is within the rural upper reaches of the Stoke Brook, a tributary to the Bear Brook and River Thame. The study area covers the reach of the Stoke Brook in the area of Stoke Mandeville, as shown in Figure 1.

Figure 1: Location and extent of the Stoke Brook model



2.1.2 Figure 2 presents a more detailed view of the study area, including an overview of the topography generated using light detection and ranging (LiDAR) data. The natural valley and floodplain are clearly defined, with the artificial channel to the mill pond (the mill stream), passing along high land to the north of the floodplain. Under flood conditions, the natural channel and floodplain would be expected to carry the majority of the flow.

Figure 2: Topography of the Stoke Brook study area



2.2 Hydrological context

2.2.1 The Stoke Brook has a catchment size of 7.9km^2 at the culvert beneath the Princes Risborough to Aylesbury Line. Catchment descriptors have been obtained from the Flood Estimation Handbook (FEH) CD-ROM (v3). The catchment is relatively shallow (index of catchment steepness (DPSBAR) = 36) for a headwater catchment, with the longest drainage path of 7.9km and low aspect variation (0.48) suggesting narrow, relatively straight, valleys. The average drainage path length of 4.0km suggests that the catchment is fairly uniform in width along its length.

2.2.2 The climate and soils descriptors show that the catchment is relatively dry, with low annual rainfall (standard average annual rainfall (SAAR) = 665) and a low proportion of

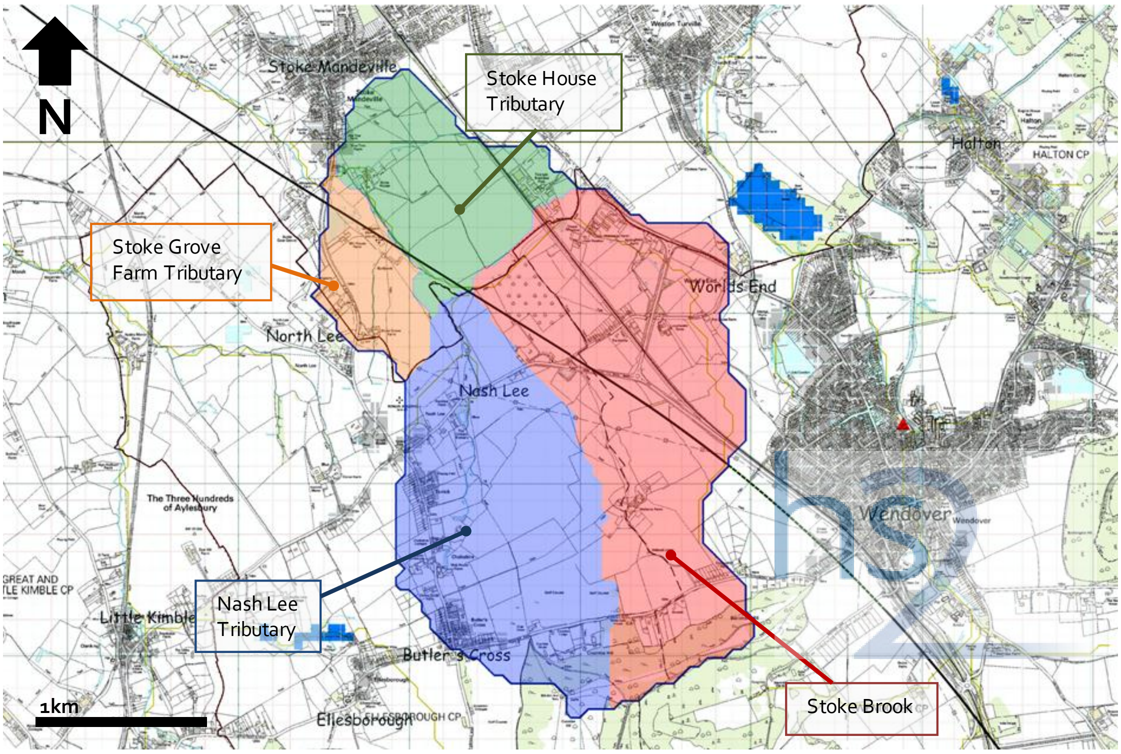
time annually where soils are 'wet' (index of proportion of time that soils are wet (PROPWET) = 0.32). There is no recorded attenuation due to reservoirs or lakes within the catchment (flood attenuation by reservoirs and lakes (FARL) = 1).

2.2.3 The catchment is 'essentially rural' with an urban extent value (in the year 2000) of 0.027, comprising part of Butler's Cross, Chalkshire, Terrick and Nash Lee, all along the western edge of the catchment.

2.2.4 The natural catchment is composed of four separate watercourse inflows which converge at Risborough Road, as described and as shown in Figure 3:

- the Stoke Brook main catchment (shown in red) which originates between Wendover and Ellesborough, with the first formal channels appearing on Ordnance Survey mapping around World's End. The watercourse enters the study area at Triangle Business Park, near World's End. The design catchment for this inflow is taken at the confluence with the tributary from Nash Lee;
- the tributary from Nash Lee (shown in blue) which rises around Terrick near Butler's Cross, passing through Nash Lee as it enters the study area. The design catchment for this inflow is taken at the confluence with the Stoke Brook;
- the tributary at Stoke House (shown in green) which rises north of Triangle Business Park and joins the Stoke Brook upstream of Risborough Road, combining with flows from the mill stream at Stoke House. The design catchment for this inflow is taken at Risborough Road; and
- the tributary from Stoke Grove Farm (shown in orange) which rises east of North Lee, and flows north to join the Stoke Brook around St Mary's Chapel. In order to include all flows into the Stoke Brook between the Nash Lee Orchard confluence and Risborough Road; the design catchment for this inflow is taken as the remainder of the full catchment having removed the previous three catchments.

Figure 3: Stoke Brook catchment overview map



2.2.5 A final inflow to be applied as a spread lateral inflow arises due to rainfall on the remainder of the catchment from Risborough Road to the downstream model boundary. This is defined by removing the area of catchment upstream of Risborough Road from the full catchment at the downstream boundary.

2.3 Hydrological assessment

2.3.1 An initial hydrological assessment was undertaken across the entire Stoke Brook catchment to the downstream boundary at the Princes Risborough to Aylesbury Line crossing to determine likely peak flows within the watercourse and to assess the performance of the two main flood estimation procedures in relation to one another. A full routed rainfall-runoff output such as that derived using the Revitalised Flood Hydrograph (ReFH) rainfall runoff methodology is required for time-varying hydrodynamic modelling. The ReFH outputs can be scaled if required to fit derived hydrograph peaks obtained using the peak flood flows calculated using the statistical growth curve method.

Revitalised flood hydrograph rainfall runoff method

2.3.2 The ReFH was applied using the spreadsheet implementation (v1.4) developed by HR Wallingford together with the catchment descriptors obtained from the FEH CD-ROM. No rainfall or flow data was available for the catchment and all ReFH design standard parameters were therefore applied without observed or analogue adjustments. A model timestep of 30mins and critical storm duration of 7.5hrs was used in the analysis of the full catchment.

2.3.3 The FEH depth-duration-frequency rainfall modelling for the catchment was used to obtain total rainfall volumes for each design storm which was spread across the storm duration of 7.5hrs using the winter storm profile due to the rural nature of the catchment. Seasonal correction and areal reduction factors of 0.69 and 0.96 were applied with resultant total and peak storm rainfall as shown in Table 1.

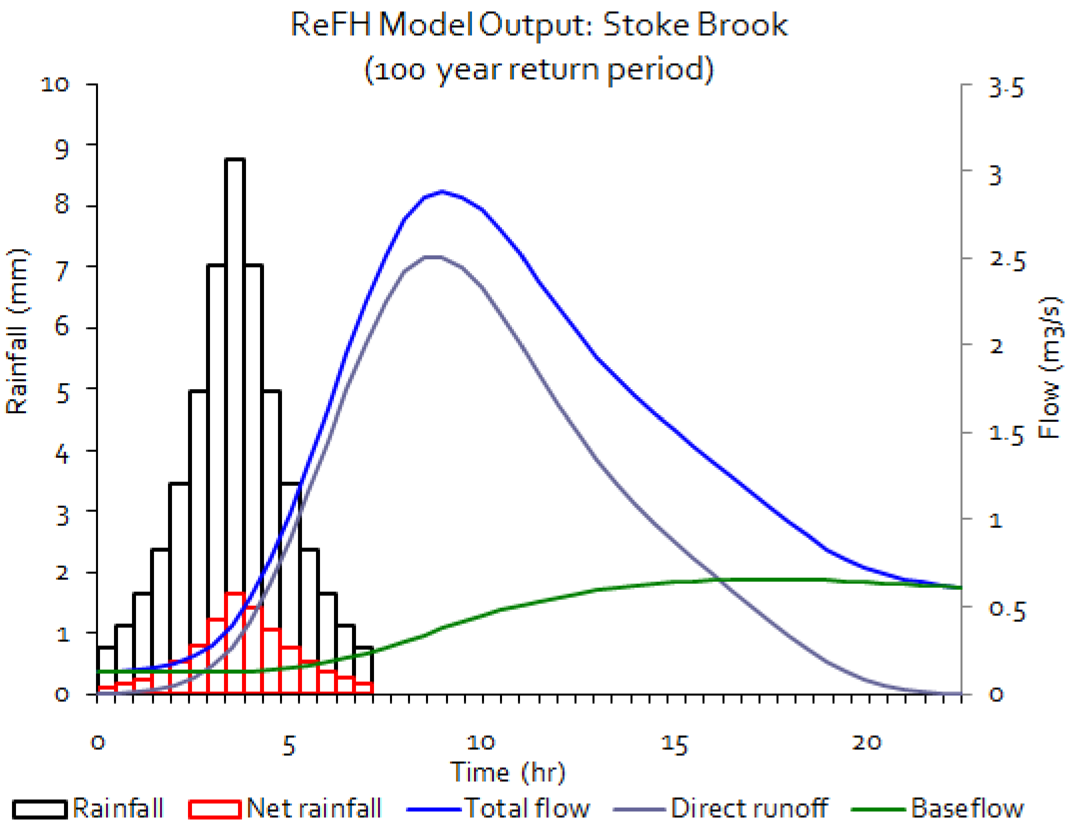
2.3.4 The loss, routing and baseflow models use the catchment descriptors and standard ReFH models and parameters in the absence of any gauged flow information for the watercourse. The unit hydrograph time to peak of 4.4hrs indicates a relatively slow flood response for the catchment size which would ultimately result in lower peak flows than for a flashier catchment. Calculated initial baseflows are very low at approximately 0.1m^3/s. An initial soil moisture deficit of 89mm was calculated. The combined models were applied to the calculated input rainfall by scaling and aggregating the unit hydrograph calculated using the loss and routing models. The baseflow hydrograph was then combined with the storm hydrograph to give a design hydrograph for each return period.

Table 1: Stoke Brook revitalised flood hydrograph rainfall volumes and peak flows

Return period	**Depth-duration-frequency rainfall (mm)**	**Design rainfall (mm)**	**Peak rainfall (mm)**	**Peak runoff (m^3/s)**
2 years	25.7	17	2.9	1.00
10 years	41.9	27.8	4.7	1.60
20 years	50.6	33.6	5.7	1.93
30 years	56.3	37.4	6.4	2.12
50 years	64.5	42.8	7.3	2.41
100 years	77.3	51.4	8.8	2.88
1,000 years	141.1	93.7	16.0	5.68

2.3.5 The 1 in 100 years return period (1% annual probability) rainfall event results in a peak runoff rate of 2.9m^3/s. The rainfall hyetograph, showing distribution of rainfall over time, and corresponding fluvial flood hydrograph are presented in Figure 4.

Figure 4: Stoke Brook (whole catchment) ReFH hydrograph for the 1 in 100 years return period event



Flood estimation handbook revised statistical method

2.3.6 A full statistical analysis was undertaken using WINFAP-FEH version 3.0.003. An initial pooling group was selected from the HiFlows database v.3.1.2 with an initial combined record length of 750 years. The initial, unfiltered pooling group was statistically strongly heterogeneous with a heterogeneity statistic value of 5.9. Records were initially removed on the basis of geographical and associated meteorological variation with three from Ireland removed, one from Scotland, two from Devon and two from the far north-east of England. One record was removed due to a short record length (5 years) and a second due to low confidence in the rating curve due to early drowning of the weir.

2.3.7 As a result of the removal of the above stations from the pooling group the total years of record dropped below the recommended 500 (to achieve a statistically significant fit to a return period of 100 years). Eleven further stations were considered for inclusion with five excluded on the grounds of geographical location and one excluded due to a high degree of attenuation within the catchment (FARL=0.866). The resulting pooling group was 'possibly heterogenous' with an H2 value of 1.7. Further inspection of the remaining stations suggested that the remaining outliers were all sufficiently similar to the Stoke Brook catchment in terms of the relevant catchment descriptors to be retained within the analysis.

2.3.8 The pooling group "Goodness of Fit" test indicated that the combined growth curves fit the typical UK growth curve model with an extremely close fit to the generalised logistic distribution (Z=0.0433). The final pooling group is presented in Table 2.

Table 2: Stoke Brook final pooling group

Station	**Years of record**	**Area (km^2)**	**Standard average annual rainfall (mm)**	**Flood attenuation due to reservoirs and lakes**
Stoke Brook	n/a	7.88	665	1
27051 (Crimple at Burn Bridge)	37	8.15	855	1
44009 (Wey at Broadwey)	32	7.95	894	1
26802 (Gypsey Race at Kirby Grindalythe)	10	15.85	757	1
25019 (Leven at Easby)	31	15.07	830	1
27073 (Brompton Beck at Snainton Ings)	29	8.06	721	1
44006 (Sydling Water at Sydling St Nicholas)	35	12.06	1030	0.944
28033 (Dove at Hollinsclough)	30	7.93	1346	1
27010 (Hodge Beck at Bransdale Weir)	41	18.84	987	1
44008 (South Winterbourne at Winterbourne Steepleton)	30	20.17	1012	1
36010 (Bumpstead Brook at Broad Green)	42	27.58	588	0.999
33045 (Wittle at Quidenham)	41	27.55	608	0.974
25011 (Langdon Beck at Langdon)	23	12.79	1463	1
22003 (Usway Burn at Shillmoor)	13	21.87	1056	1
29009 (Ancholme at Toft Newton)	35	29.52	616	0.997
41020 (Bevern Stream at Clappers Bridge)	40	35.42	886	0.993
25003 (Trout Beck at Moor House)	36	11.46	1904	1
27032 (Hebden Beck at Hebden)	43	22.2	1433	0.997
44809 (Piddle at Little Puddle)	16	31.27	1004	1
76011 (Coal Burn at Coalburn)	32	1.63	1096	1
25012 (Harwood Beck at Harwood)	40	24.58	1577	1

2.3.9 A growth curve for the Stoke Brook was therefore constructed using the generalised logistic distribution and a median annual flow (QMED) of $0.78m^3/s$ calculated from catchment descriptors. A minor urban adjustment was applied based on an urban

extent value for 2013 of 0.03 and a corresponding urban adjustment of 1.048 (Kjeldsen et al, 2008[1]). A 100 year return period flood flow of 2.7m^3/s was indicated.

2.3.10 The nearest HiFlows gauging station to the subject site is on the River Ray approximately 17km away. As a tributary of the Cherwell, rather than the Thame, the Ray is within a neighbouring catchment of the same river basin although it is 17km from the Stoke Brook catchment. At only 21km^2 in catchment area it is very similar in terms of altitude, geographical orientation, drainage path length and slope. A potential alternative donor site is on the River Thame downstream, however, at 441km^2 in catchment area is not suitable for use as a donor catchment due to the very different hydraulic characteristics associated with such a variance in catchment size.

2.3.11 Kjeldsen et al.[1] found that geographical distance is the most important factor in the selection of donor and analogue site, and the River Ray station was therefore used to adjust the flood frequency curves. The ratio of QMED estimated from catchment descriptors (4.3m^3/s) and from AMAX data (5.4m^3/s) for this station is 1.26. Using the latest adjustment procedure as documented by Kjeldsen et al.[1], the correction factor (weighted by geographical distance) is 1.07. The statistically calculated peak flows are presented in Table 3.

Table 3: Stoke Brook statistical peak flows

Return period	Peak flow (m^3/s) catchment descriptors	Peak flow (m^3/s) adjusted
2 years	0.78	0.83
10 years	1.41	1.51
20 years	1.73	1.85
30 years	1.94	2.08
50 years	2.23	2.39
100 years	2.70	2.89
100 year + 20%	3.24	3.47
1,000 years	5.03	5.38

2.3.12 There is a very strong correlation between the statistically estimated peak flood flows and those derived using ReFH especially at the 100 year return period. The results of the FEH statistical analysis increase confidence in the ReFH estimates of flood flow which was therefore taken forward to provide modelled inflows.

Modelled sub-catchment inflows

2.3.13 Due to the four separate inflows into the Stoke Brook within the study area (as described in paragraph 2.2.4 above), in order to accurately model the watercourse each sub-catchment inflow must be applied separately at the relevant boundary

[1] Kjeldsen, Jones, Bayliss (2008). *Improving the FEH statistical procedures for flood frequency estimation*. EA/DEFRA report SC050050

inflow location. Consequently, it is necessary to divide the catchment into the component parts to obtain each separate inflow.

2.3.14 The catchment descriptors for each sub-catchment were extracted by adding, or subtracting, component parts using the FEH CD-ROM to extract intermediate catchment characteristics along the watercourse. Area-weighted averages or specific adjustment procedures as detailed in the FEH volume 5[2] were used to create catchment descriptor files for each of the five component catchments as presented in Table 4.

2.3.15 Each modified catchment descriptor file was imported directly into the hydraulic model and applied to the relevant boundary locations to enable calculation of the relevant runoff modelling parameters at each inflow.

Table 4: Key model catchment descriptors for the Stoke Brook and sub-catchments

Model catchment descriptor	Stoke Brook (direct)	Nash Lee tributary (direct)	Stoke House tributary (derived)	Stoke Grove tributary (derived)	Lateral inflow (derived)
AREA	2.70	2.14	0.92	0.50	1.54
BFIHOST	0.726	0.807	0.516	0.529	0.499
DPLBAR	2.04	1.63	0.96	0.68	1.27
DPSBAR	45.5	51.7	12.2	18.0	17.7
FARL	1.0	1.0	1.0	1.0	1.0
FPEXT	0.097	0.091	0.180	0.124	0.107
FPDBAR	0.549	0.583	1.02	1.03	0.85
PROPWET	0.32	0.32	0.32	0.32	0.32
SAAR	684	684	645	639	628
SPRHOST	26.1	17.9	4.22	41.0	44.1
URBEXT2000	0.000	0.027	0.005	0.049	0.082

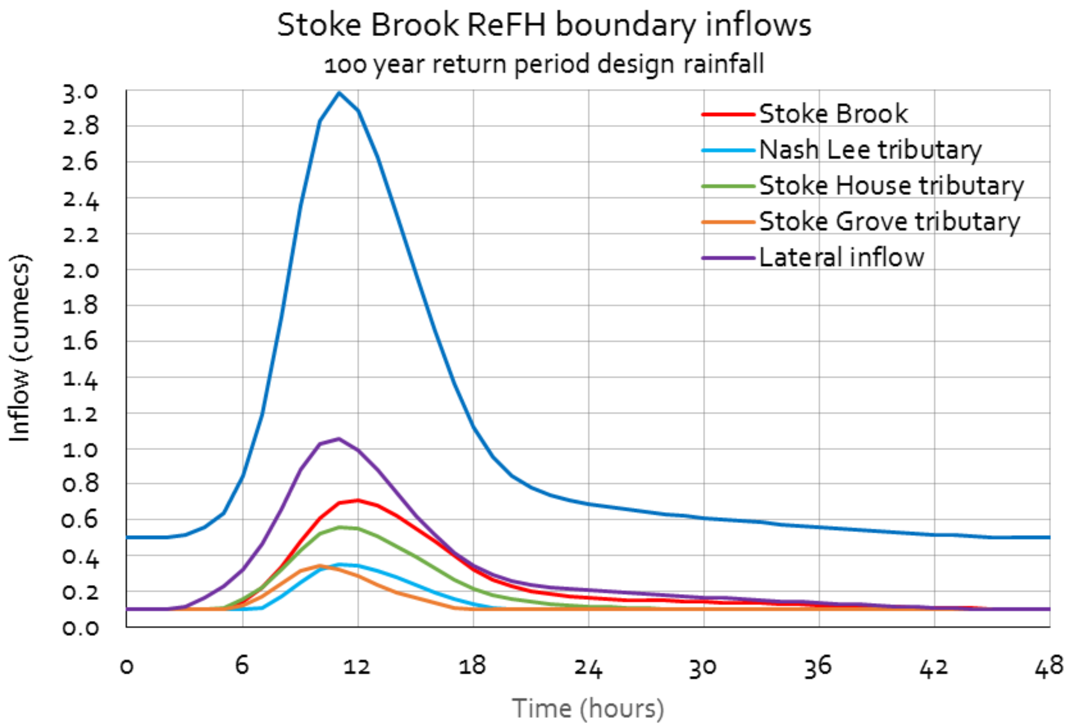
2.3.16 When modelling a small catchment with a variety of inflows it is reasonable to assume that each catchment will experience the same rainfall intensity rather than each being subject to the calculated critical storm for each inflow, which could vary widely between catchments. In this case the critical storm calculated for the full catchment to the railway crossing has therefore been applied to each inflow catchment with the ReFH routing model used to determine peak river flows. Due to the compact nature of the overall catchment the whole catchment is modelled to experience the same storm simultaneously.

2.3.17 Each sub-catchment inflow was extracted from the hydraulic model in order to verify the approach described above. Inflow hydrographs were extracted for the 100 year

[2] Institute of Hydrology (1999), *Flood Estimation Handbook*.

design rainfall event and combined to create an instantaneous inflow hydrograph, as presented in Figure 5. The peak instantaneous inflow was found to be 2.99m^3/s which corresponds well with the peak flows calculated for the entire catchment.

Figure 5: Stoke Brook ReFH inflows for the 1 in 100 years return period design rainfall



3 Baseline hydraulic modelling

3.1 Model definition

3.1.1 The hydraulic model was compiled in order to inform the design and assess potential impacts within the Stoke Brook, predominantly at the 1 in 100 years return period (1% annual exceedance probability) flood, both in the present day and future case (i.e. including a 20% increase to inflows as recommended in the NPPF). The extreme 1 in 1,000 years return period (0.1% annual exceedance probability) flood has also been modelled.

3.1.2 The risk to the Proposed Scheme and potential effects on flooding are limited in scope primarily to the catchment above Risborough Road. Consequently, the detailed modelling exercise has focussed on this section of the Stoke Brook with the downstream channel and floodplain continued to approximately 500m upstream of the Princes Risborough to Aylesbury Line. The floodplain and channel downstream of Risborough Road are uniform in terms of slope and geometry and relatively free of restriction and are therefore a good basis for application as a normal depth downstream boundary. The final cross section is upstream of the complex fish ponds and moat system at Moat Farm. Hydraulic structures and floodplain flow mechanisms have not been added or optimised within this area downstream of Risborough Road.

3.1.3 The Stoke Brook has been modelled in Infoworks RS2D v13.5.3. A digital terrain model (DTM) was compiled using the 0.2m resolution LiDAR data and used to extract watercourse cross sections initially spaced at 50m intervals. A fully one-dimensional model was built including the Risborough Road culvert to gain an initial understanding of flooding mechanisms along the study reach. Additional sections were added and refined as necessary around junctions, structures, and in areas of high gradient to ensure model stability.

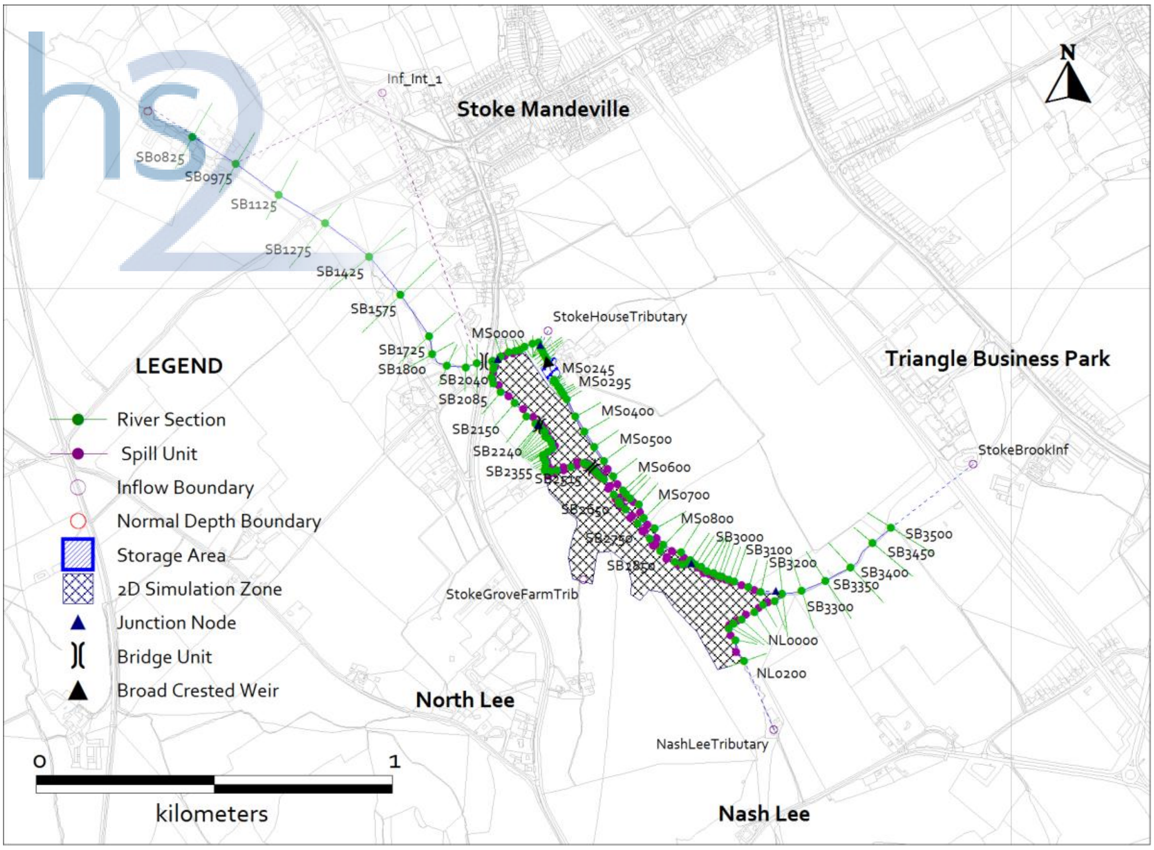
3.1.4 A site walkover survey to the Stoke Brook was undertaken in December 2012. Key hydraulic structures were inspected and measured and the condition of the channel and floodplain were observed in order to identify areas of specific interest and to assess potential roughness and structural coefficients. During the walkover survey it was noted that under normal flow conditions the mill stream spills into the natural channel at two locations, at the bifurcation of the two channels and approximately 250m downstream of the bifurcation north-east of the St Mary's Church burial ground. These were included in the model as overbank spill units defined using on-site observations.

3.1.5 Following initial high flow model runs it became clear that the tributary stream from Nash Lee lies potentially across the floodplain flow pathway of the Stoke Brook and it was therefore necessary to include the watercourse specifically within the model. It was also clear that there is interaction between the two Stoke Brook channels and along the southern floodplain. The use of overbank spills and storage areas to define these interactions was investigated, however, due to the unconfined gradient of the southern floodplain it was not possible to accurately represent this area within a one-dimensional model to accurately determine floodplain water levels.

3.1.6 Two separate two-dimensional floodplain flow domains were defined. A central floodplain area comprises the land between the two channels of the Stoke Brook. A southern floodplain area is bounded by the Nash Lee Tributary and Stoke Brook natural channel covering the downstream extent of the tributary from Stoke Farm. Overbank spills were defined along the top-of-bank (located using the 0.2m resolution LiDAR) to link the one-dimensional model with the two-dimensional domains. The mesh resolution was increased in areas of particular interest such as close to the river channel and along flow pathways. The overbank spill north-east of St Mary's Church burial ground was included in the central floodplain simulation area.

3.1.7 At the highest return period flood events there is interaction between the floodplain flow from the Stoke Brook in the southern floodplain area and the flow in the tributary from Stoke Grove Farm. The Stoke Grove Farm tributary inflow was therefore converted to a two-dimensional domain inflow at the southern extent of the tributary within the southern floodplain area to account for combined effects.

Figure 6: Overview of the Stoke Brook model



3.1.8 The final model schematic is presented in Figure 6. The initial 0.2m resolution DTM was resampled to 0.5m resolution for the final model runs to moderate the variability in ground level within the two-dimensional domain and improve model stability and volume conservation without significantly losing accuracy. The one-dimensional geometry was left unchanged.

3.2 Model boundaries

3.2.1 The initial model build covered the channel of the Stoke Brook together with the Stoke House mill stream channel from immediately downstream of the railway culvert at Triangle Business Park to the channel downstream of the Princes Risborough to Aylesbury Line. The Nash Lee, Stoke House and Stoke Grove Farm inflows were applied at the respective confluence locations for these watercourses. The full sub-catchment flows were conservatively applied at each inflow boundary location to ensure that all catchment rainfall is taken into account.

3.2.2 The Stoke Brook and floodplain between Risborough Road and the Princes Risborough to Aylesbury Line are relatively uniform in terms of shape, slope and roughness for a significant distance (approximately 1km) and a normal depth downstream boundary is therefore appropriate. The slope and geometry was taken directly from the 0.2m LiDAR data.

3.3 Roughness coefficients and structural definitions

3.3.1 The state of the watercourse and floodplain was observed during the site walkover survey and Manning's roughness values were defined on the basis of these observations. The channel is characterised by a good clear flow area, however, side slopes and bed area are irregular and lightly vegetated. Cross section variations are common but gradual. The floodplain area, though varied, is characterised by relatively dense vegetation, largely weeds, and moderate surface undulations. A value of 0.045 was applied to all river channels with a value of 0.07 used for the floodplain areas in accordance with standard texts (Chow[3]). For the two-dimensional areas a value of 0.07 was chosen to reflect the density of weeds and scattered shrubs observed during the site walkover survey.

3.3.2 All overbank spill units in the model were initially set with a discharge coefficient of 1.0 to reflect the roughness of the floodplain. During model development it was found that applying the lower discharge coefficient to connecting spill units between the one-dimensional and two-dimensional domains resulted in calculation errors and discharge coefficients for connecting spill units were consequently raised back to the default value of 1.7. Since these spill units have an effective hydraulic length of close to zero and with roughness losses accounted for within the two-dimensional domain this is an acceptable change.

3.3.3 The key hydraulic structures within the main study area are the Risborough Road embankment and culvert and the Stoke House millpond and weir structures. Measurements were taken on-site and used to define the structures in the model. Other structures inspected included the two footpath crossings of the Stoke Brook natural channel, the two road bridges over the mill stream which carry the drive to Stoke House and two further footbridges across the mill stream. Initial model runs showed that since the majority of flow passes along the natural channel of the Stoke Brook the bridges across the mill stream do not have any significant hydraulic effects

[3] Ven Te Chow (1959, 2009 edition). *Open-channel hydraulics*, The Blackburn Press, Caldwell, NJ, USA.

and flood water levels in the mill stream were not affected by the presence or otherwise of the hydraulic units across all return periods. In order to reduce computational complexity and thus improve model stability they were removed from the final model. The two footpath crossings of the natural channel were retained.

3.3.4 The Risborough Road culvert was defined using a United States bureau of public roads bridge hydraulic unit. A 2.5m wide culvert with a soffit height of 97m above Ordnance Datum (AOD) was defined with the upstream channel section taken from the 0.2m LiDAR. Due to the channel confluence upstream of the culvert an additional dummy section was included to assist in model stability. Since initial model runs showed that the Risborough Road embankment does not overtop, no inline spill was included at this location.

3.3.5 The Stoke House mill pond was defined as a storage area with plan area measured from the LiDAR information. Initial water levels were taken from the LiDAR and the same plan area was applied for all storage intervals. A single broad-crested weir was defined to represent the spillway with dimensions and coefficients based on site observations.

3.3.6 The two footbridges were represented using the arch bridge hydraulic unit combined with inline spill units where necessary. Structural dimensions were taken from the 0.2m LiDAR and site observations.

Initial conditions

3.3.7 The linked hydraulic model was found to be relatively unstable at low flows particularly at the start of the simulation. In order to improve initial stability within the model a two-step process was undertaken to set the initial conditions for the design model runs.

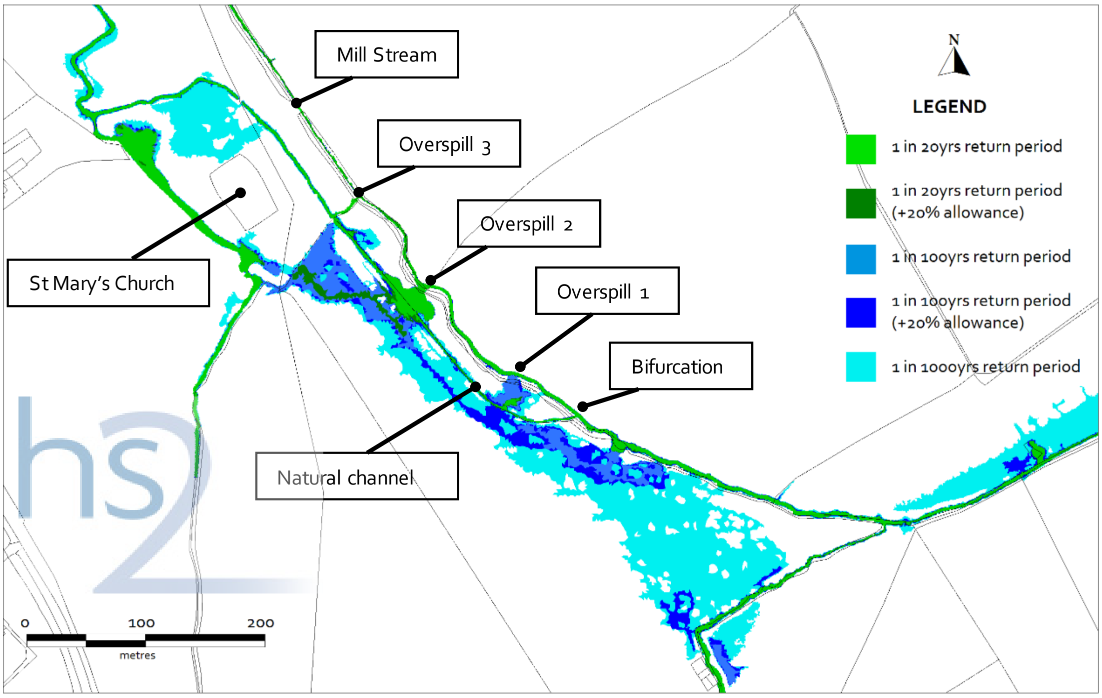
3.3.8 Initial conditions were defined for every cross section by extracting the depth, velocity and Froude number for a $0.1m^3/s$ flow at each section from each respective Manning's tabulation and extrapolated to set conditions at each structure. A steady state (direct method) simulation was run at hydrological time 2hrs using the one-dimensional components of the model with overbank spills removed and weir and pond units used to define the two overflow channels along the mill stream and the mill pond. These results were then used to run a full unsteady state simulation using the one-dimensional components of the model with only the central overbank spill represented using a weir. Initial conditions were taken from the unsteady state simulation at a time of 2.4hrs when modelled inflows and outflows had stabilised but before any significant inflows were applied. In addition to setting initial conditions these two model networks were used to optimise the one-dimensional model to remove all instabilities and fluctuations prior to running the fully linked model. Further initial conditions were applied within the two-dimensional mesh where the one-dimensional results showed that overbank spill units were operational along the overflow channel north-east of St Mary's Church and along the channel of the Stoke Farm tributary where a 10mm initial depth was applied based on site observations.

3.4 Baseline model results

Flooding mechanisms

3.4.1 The channel of the Stoke Brook, along the natural channel and along the mill stream, is relatively wide and deep considering the proximity to the head of the catchment and consequent low flows in the watercourse. As a result, out-of-bank flow even in extreme (1 in 1,000 years return period) flood events is limited. All significant flooding occurs upstream of the confluence with the tributary from Stoke Grove Farm as shown on drawing WR-06-021b and WR-05-021b for the 1 in 20 years and the 1 in 100 years + 20% events respectively (Volume 5, Water Resources and Flood Risk Map Book). Flood outlines from Nash Lee to the confluence are presented in Figure 7.

Figure 7: Flood extent outlines upstream of the Stoke Grove Farm tributary



3.4.2 All flooding occurs either as a result of overtopping of the mill stream into the natural channel or from flow along the southern floodplain. The model shows that, in addition to the two previously identified overflows from the mill stream (at the bifurcation and overspill 3), there are two other locations where flow spills from the mill stream to the natural channel. Both lie between the originally identified overflows at 60m (overspill 1) and 180m (overspill 2) downstream of the channel bifurcation. Overspill 1 is active at a return period of 1 in 100 years (1% annual exceedance probability) while overspill 2 is active at significantly lower flows and is present in the 1 in 20 years (5% annual exceedance probability) event.

3.4.3 Flow within the southern floodplain arises initially due to out-of-bank flooding immediately opposite overspill 2. Flow is in a westerly direction joining with flows from the Stoke Grove Farm tributary. During events with a return period of 100 years or greater flow also returns to the main channel opposite overspill 3. Bypassing of the natural channel upstream of the bifurcation occurs during events with return periods of 100 years or greater returning to the channel downstream of the bifurcation, or in the 1 in 100 years return period event including an allowance for climate change and the 1 in 1,000 years return period event continues along the southern floodplain.

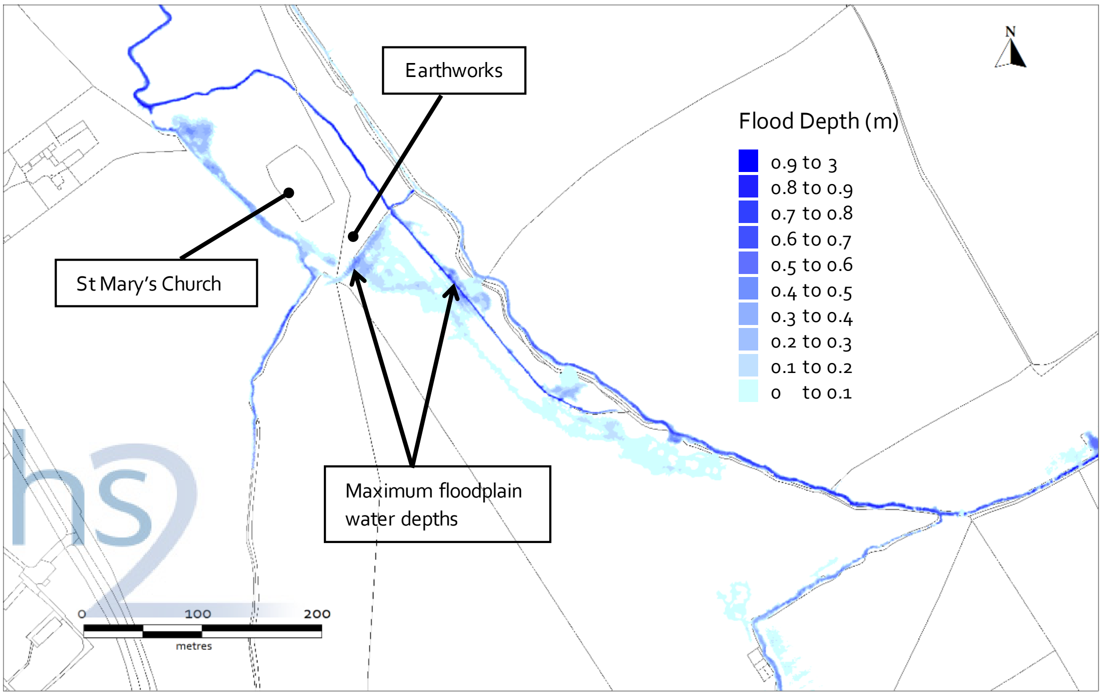
3.4.4 In the 1 in 1,000 years return period event overtopping of the Nash Lee tributary occurs, with extensive, though shallow, flooding along the southern floodplain. There is also uniform out-of-bank flooding upstream of the Nash Lee confluence and overland flooding due to backing up behind the culvert at the footpath crossing of the Stoke Brook immediately downstream of St Mary's Church.

Flood depths and levels

3.4.5 Modelled flood water depths were computed by the software for both the one-dimensional and two-dimensional model areas. Flood depth grids were combined to create overall flood depth maps. Figure 8 shows the flood depths for the 1 in 100 years return period event including an allowance for climate change of 20% added to the flow.

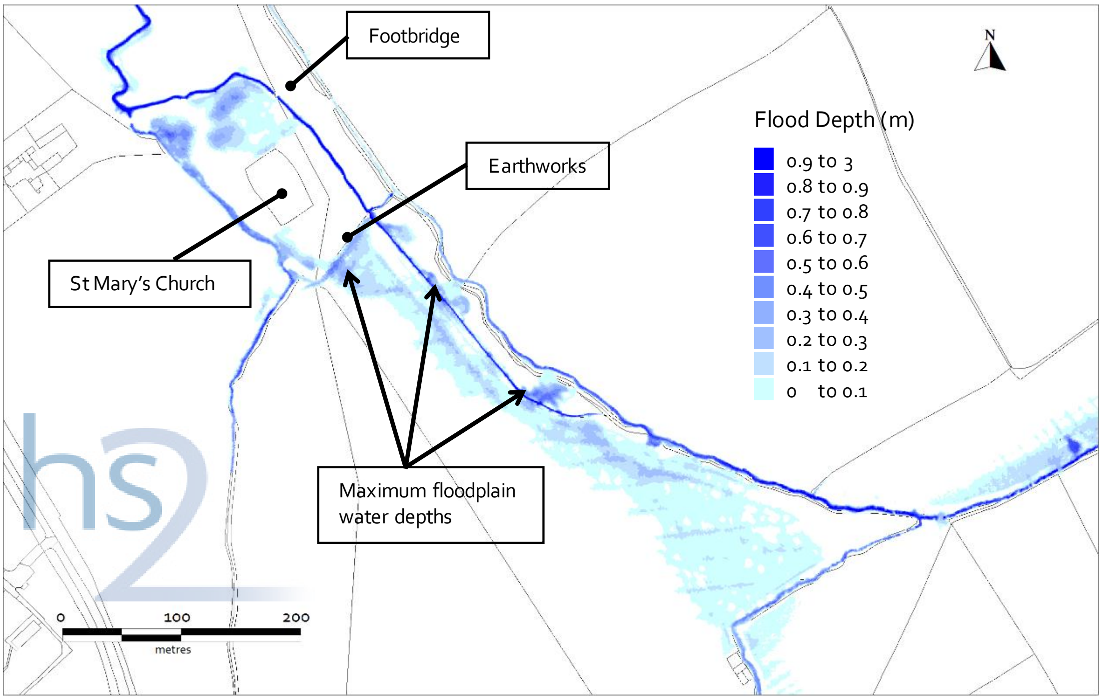
3.4.6 The majority of the out-of-bank flooding in the 1 in 100 years return period event including an allowance for climate change is less than 0.1m in depth. Maximum flood depths away from the identifiable watercourse channels are 0.5m occurring adjacent to the Stoke Brook natural channel within the central floodplain area and along the south-eastern edge of the raised earthworks south-east of St Mary's Church in the southern floodplain.

Figure 8: Modelled flood depths upstream of Stoke Grove Farm tributary confluence in the 1 in 100 years return period (including an allowance for climate change) event



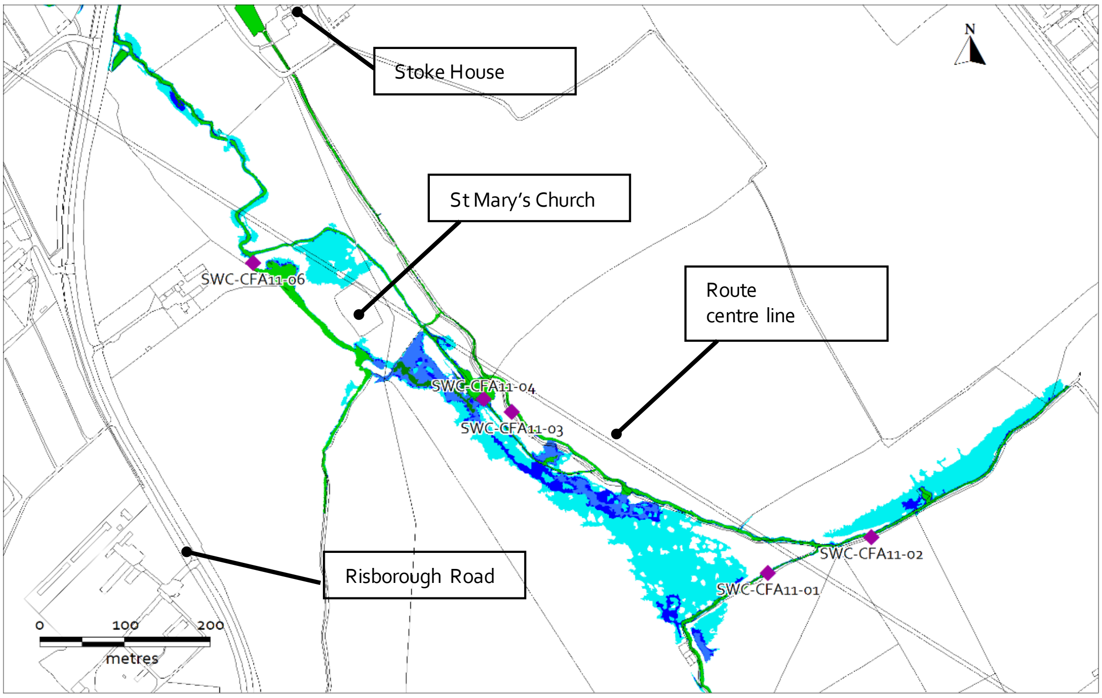
3.4.7 Similarly, estimated flood depths in the 1 in 1,000 years return period event are presented in Figure 9. Corresponding maximum flood depths are 0.6m in both the central floodplain and on the south-eastern side of the raised earthworks. In addition, there are areas of ponding up to depths of 0.5m in the area of flooding around the footbridge near St Mary's Church and 0.6m upstream of the confluence of the Stoke Grove Farm tributary and the Stoke Brook.

Figure 9: Modelled flood depths upstream of Stoke Grove Farm tributary confluence in the 1 in 1,000 years return period event



3.4.8 Flood water levels have been extracted from the model at the upstream extent of each crossing location as shown in Figure 10.

Figure 10: Observation points location plan



3.4.9 The corresponding modelled maximum flood water levels extracted from the model for all return periods are presented in Table 5.

Table 5: Baseline modelled maximum flood water levels

Surface water crossing reference	Description	Water level (m AOD)		
		1 in 20 years	1 in 100 years (+20%)	1 in 1000 years
SWC-CFA11-01 (NL-0015)	Nash Lee tributary foot of west-side embankment	103.03	103.14	103.25
SWC-CFA11-02 (SB3300)	Stoke Brook upstream of Footpath ELL/20 overbridge	102.96	103.13	103.33
SWC-CFA11-03 (MS0800)	Mill stream foot of west-side embankment	101.83	101.93	101.95
SWC-CFA11-04 (SB2800)	Stoke Brook foot of west-side embankment	100.25	100.41	100.52
SWC-CFA11-06 (two-dimensional mesh)	Stoke Grove Farm tributary foot of west side embankment	98.33	98.45	98.67

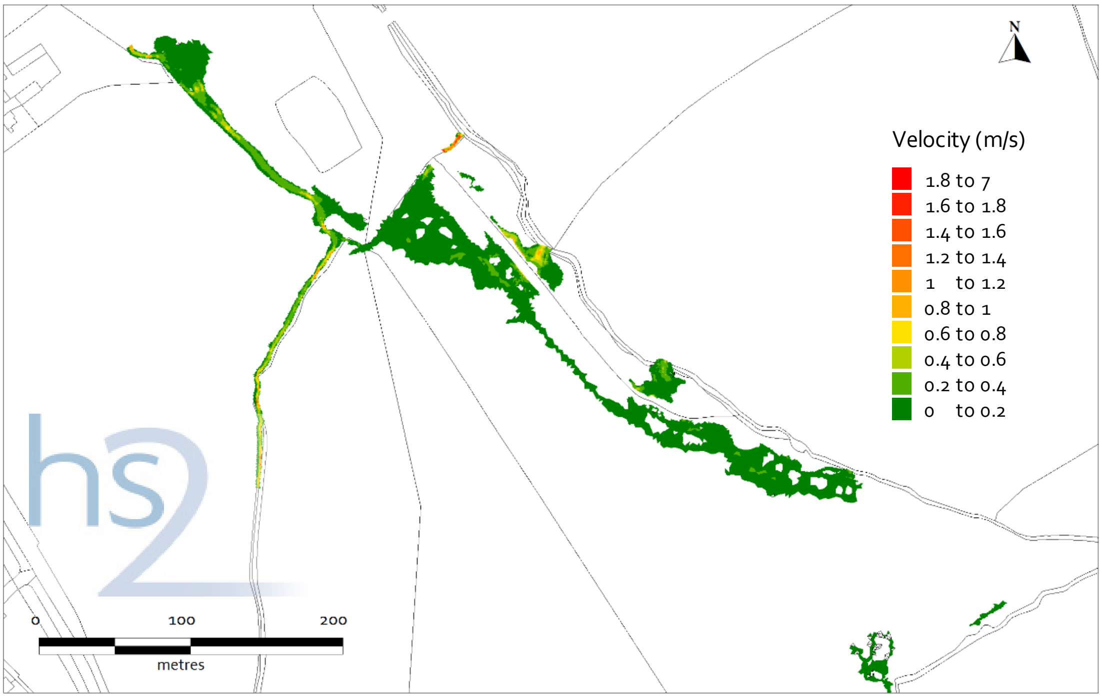
Floodplain extents

3.4.10 Floodplain extents for the 1 in 20 year and 1 in 100 year plus climate change baseline scenarios are shown in WR-06-021b and WR-05-021b respectively (Volume 5, Water Resources and Flood Risk Map Book).

Flood velocities

3.4.11 Flood flow velocities were extracted from both the one-dimensional and two-dimensional model zones. Due to the different computational methods spatial velocity data is only available for the two-dimensional (floodplain flow) component of the model. Floodplain flow velocities for the 1 in 100 years return period event including an allowance for climate change are presented in Figure 11.

Figure 11: Modelled floodplain velocities during the 1 in 100 years return period flood event (including an allowance for climate change)



3.4.12 Velocities are generally low within the southern floodplain area with maximum velocities of 0.3m/s. At the overspills and within the central floodplain, due to the high potential energy inherent to spillway flooding, velocities peak at 1m/s. Flow velocities within the channels range between 0.5m/s and 1m/s. Note that peak velocities do not necessarily coincide with peak flood water levels.

Sensitivity testing

3.4.13 In order to verify the model results sensitivity analyses were undertaken varying the following model parameters within the 1 in 100 years return period simulation including an allowance for climate change:

- Manning's roughness in the two-dimensional mesh;
- Manning's roughness in the one-dimensional components;
- Manning's roughness in both the one-dimensional and the two-dimensional mesh; and
- the channel slope used in the computation of normal depth at the downstream boundary.

3.4.14 Manning's roughness values in the two-dimensional mesh were varied by 20% (i.e. applying values of 0.056 and 0.084) as well as a single simulation applying a value of 0.035 (the lowest recommended value for pasture). Reducing the roughness had the general effect of slightly reducing flood levels within the two-dimensional area with maximum reductions of 66mm. All reductions in flood depths of greater than 10mm were along the Stoke Grove Farm tributary channel and there were no significant

changes in the flooding extents. Slight increases in flood depths were present close to the natural channel at the overspill locations due to slightly increased flow velocities within the mesh but no increases were noted in the extents of flooding or depths in the one-dimensional components of the model. Similar changes were present for the increased roughness scenario. The sensitivity of the model to roughness in the floodplain is very low. Flood levels reduce with reductions in roughness so the choice of 0.07, which is at the higher end of the recommended range, is conservative.

3.4.15 Simulations were run with Manning's roughness coefficients varied by 20% within only the one-dimensional components of the model and with the mesh roughness adjusted. As would be expected given the low sensitivity to floodplain roughness the results were similar for the two tests with key changes to flood water levels present within the one-dimensional components. A reduction in roughness values to 0.028 for the channel and 0.056 for the floodplain resulted in a general reduction in flood water levels in the channel due to improved conveyance capacity. The maximum reduction in flood levels was 125mm with reductions most pronounced along the natural channel of the Stoke Brook. Due to these flood level reductions out-of-bank flows were reduced with a consequent reduction in floodplain extent particularly in the southern floodplain as shown in Figure 12. There was also an increase in flood water levels in the mill stream downstream of the overspill locations. This arises due to the lower flood water levels at each spill which result in lower flow volumes over each spill. As a result, flow volumes continuing along the mill stream increase with a corresponding increase in water levels. The maximum increase was 68mm, however, all increases in water level were contained in channel so flood extents were unaffected. Corresponding changes were present for the increased roughness scenario, which result in increased extents between the Nash Lee tributary and the southern floodplain, due to increased water levels and overtopping within the channel of the tributary.

Figure 12: Effect of roughness variations within the one-dimensional components on flooding extents for the 1 in 100 years return period event including an allowance for climate change.

3.4.16 As is to be expected in hydraulic models with relatively shallow flow the model shows moderate sensitivity to the value of Manning's roughness used within the one-dimensional model components. The effect on the extent of out-of-bank flooding is significant due to the overall small volumes of floodplain flow experienced. However, roughness values have been chosen at the upper end of the recommended range (0.050 is the usual maximum for pasture, and 0.070 is the maximum value for "scattered brush with heavy weeds"). The value of 0.045 for the channel is the recommended value for a winding channel with weeds and an irregular bed. Since the model shows an increased risk of flooding at higher roughness values the choice of Manning's 'n' at the upper end of the scale is conservative.

3.4.17 The channel slope at the downstream boundary is 0.005 (1 in 200) based on LiDAR measurements. The slope used for the computation of normal depth was varied by 20% (i.e. using values of 0.004 and 0.006) to determine the sensitivity of the model to the boundary condition. Increasing the slope by 20% had no significant effect from 300m upstream of the downstream boundary demonstrating that the model is not sensitive to this parameter.

3.4.18 The results of the sensitivity tests are summarised, together with the changes in water level at each of the observation points used for analysis, in Table 6.

Table 6: Summary of model sensitivity

Location		Roughness – two-dimensional only (20%)	Roughness – one-dimensional only (20%)	Roughness – combined (20%)	Normal depth slope (20%)
Summary		Variations less than 100mm at all locations and less than 10mm away from tributary channel.	Significant extent and depth changes. Sensitive, but choice of roughness parameters is conservative.		No sensitivity from 300m upstream of boundary.
SWC-CFA11-01 (NL-0015)	-20%	none	-47mm	-47mm	n/a
	+20%	none	+42mm	+43mm	n/a
SWC-CFA11-02 (SB3300)	-20%	none	-66mm	-63mm	n/a
	+20%	none	+52mm	+55mm	n/a
SWC-CFA11-03 (MS0800)	-20%	-1mm	+4mm	+5mm	n/a
	+20%	none	-7mm	-7mm	n/a
SWC-CFA11-04 (SB2800)	-20%	-4mm	-96mm	-101mm	n/a
	+20%	+3mm	+40mm	+44mm	n/a
SWC-CFA11-06 (two-dimensional mesh)	-20%	-5mm	-63mm	-79mm	n/a
	+20%	+1mm	+43mm	+43mm	n/a

3.4.19 Although the model shows a sensitivity to the choice of Manning's roughness parameter within the one-dimensional components, the values used for the design scenario are conservatively high, and the results discussed are robust.

Model diagnostics

3.4.20 The model was run in unsteady state mode with an adaptive timestep. The minimum timestep used was 0.185s, and there were no convergence failures recorded across any simulation. The simplified computational method (used to calculate flows at high Froude numbers, i.e. supercritical flows) was used at a minority of cross sections at low flows, mostly around the Risborough Road culvert.

3.4.21 The main source of model instability within a dynamically linked one-dimensional and two-dimensional hydraulic model occurs at the spill units that compute flows into and out of the two-dimensional model domain. Instability is typically caused by flat mesh elements or elements where the spill unit is at the low point, i.e. the spill does not coincide with raised top-of-bank levels, either due to an incorrect definition or because there is no high-point at the top-of-bank. This can result in computation of flow simultaneously in both directions across the spill, with the usual result that flood volume is created, or destroyed. Similar errors can also occur within the two-dimensional domain itself.

3.4.22 A significant proportion of model development was dedicated to elimination or minimisation of these volume generation errors. Final model runs were completed with less than 0.0005m^3 of flood volume created or removed (-0.3% mass error in the 1 in 1,000 years return period simulation) within the mesh itself across all return periods, and no errors at overbank spills up to the 1 in 100 years return period including an allowance for climate change simulation. In the 1 in 1,000 years return period simulation, a total volume of 0.035m^3 was generated at overbank spills across the simulation, at one location, with a maximum volume generation of 0.001m^3 in any one time-step. This is an acceptably insignificant error.

3.4.23 To aid with one-dimensional model stability, particularly at low flows, the maximum number of iterations at any one time step was increased to 100, and an automatic Preissman slot with standard geometrical dimensions was enabled to avoid run-dry errors. No further changes were made to standard model run parameters.

3.5 Flood risk

Risk of flooding to Proposed Scheme

3.5.1 The main purpose of the modelling exercise was to redefine the baseline flood risk to generate flood water levels in order to assess the risk of flooding to the Proposed Scheme.

Table 7: Modelled maximum flood water levels and corresponding top-of-rail levels for the Proposed Scheme

		Modelled maximum flood water level (m AOD)			
Surface water crossing reference	**Description**	**1 in 20 years**	**1 in 100 years (+20%)**	**1 in 1000 years**	**Top-of-rail level**
SWC-CFA11-01 (NL-0015)	Nash Lee tributary foot of west-side embankment	103.03	103.14	103.25	105.4
SWC-CFA11-02 (SB3300)	Stoke Brook upstream of Footpath ELL/20 overbridge	102.96	103.13	103.33	105.7
SWC-CFA11-03 (MS0800)	Mill stream foot of west-side embankment	101.83	101.93	101.95	104.7
SWC-CFA11-04 (SB2800)	Stoke Brook foot of west-side embankment	100.25	100.41	100.52	104.4
SWC-CFA11-06 (two-dimensional mesh)	Stoke Grove Farm tributary foot of west side embankment	98.33	98.45	98.67	103.7

3.5.2 Table 7 presents a comparison of the modelled flood water levels with the top-of-rail levels for the Proposed Scheme. At all locations, the Proposed Scheme will be at least 2m above the 1 in 1,000 years return period (0.1% annual probability) flood water level.

Potential effects of the proposed scheme on flood risk

3.5.3 Since the Proposed Scheme will require works within the floodplain, including diversion and culverting of the watercourses, there is potential for the Proposed Scheme to have an effect on the risk of flooding in the area. Potential impacts arise due to the following:

- any construction within areas at risk of flooding will occupy floodplain storage and potentially displace floodwaters;
- linear construction across floodplains combined with culverting of watercourses could cause obstruction of flow potentially increasing the risk of flooding upstream of the constriction and reduce the risk of flooding downstream; and
- diversion of watercourses can alter the risk of flooding by changing hydraulic characteristics; for example, straightening and shortening a watercourse can lead to increased flood peaks and hence risk downstream due to reduced conveyance times and reduced energy losses.

3.5.4 At the Stoke Brook the majority of flood flow volume is contained within the watercourse channels. All crossings will be designed with sufficient capacity to convey the design flood event (1 in 100 years return period (1% annual probability) including an allowance for climate change) and all watercourse crossings are therefore effectively clear-span structures with no significant obstruction of flood flow or loss in floodplain storage. The exceptions are at overspills 2 and 3 which will be removed entirely and the flow rerouted beneath the Proposed Scheme in culverts. Therefore effects arising from obstruction of flood flow and displacement of floodwaters will be negligible.

3.5.5 The primary source of potential impacts is due to diversion of the watercourse along either side of the Proposed Scheme. These are subject to detailed design and approval from the Environment Agency and will be supported by detailed hydraulic modelling. Areas have been included within the land required for the Proposed Scheme to accommodate these channel alterations as well as replacement floodplain storage areas where appropriate.

3.5.6 Detailed hydraulic modelling of the Proposed Scheme was therefore not required at this location in order to assess the impact of the development. As this modelling exercise has been used to define baseline flood risk and present absolute flood water levels for the flood risk assessment sensitivity testing has been undertaken as set out in Section 3.4 of this report.

4 Conclusions

4.1.1 This modelling work was undertaken to refine the baseline flood risk from the Stoke Brook, and in order to identify design constraints for the proposed works to the Stoke Brook. No existing hydraulic model of the Stoke Brook was available and therefore a dynamically linked one-dimensional and two-dimensional model was constructed using InfoWorks RS2D.

4.1.2 Three main flood events have been modelled. These are the 20 year return period, the 100 year return period, with an allowance of 20% for climate change, and the 1,000 year return period flood events. Baseline model results were interrogated and compared to anticipated flood mechanisms based on the site walkover survey, and were found to be representative. Standard model parameters were applied, and numerical instability was minimal.

4.1.3 The model shows that the majority of flood flows remain within the natural channel of the Stoke Brook with a minor degree of bypassing along the southern floodplain at higher return period events. The mill stream, whilst carrying a small proportion of the flow, acts mainly as a storage channel with the majority of flow passing along the natural channel and floodplain.

4.1.4 Comparison of modelled flood water levels with proposed top-of-rail levels indicates that the Proposed Scheme will not be at significant risk of flooding from the Stoke Brook.

4.1.5 Since the majority of flood flows remain within the watercourse channels there will be only minor displacement of flood waters within the floodplain due to the Proposed Scheme which includes a large area of land set aside for replacement floodplains storage.

4.1.6 The design of the channel diversions and culverts will be undertaken to an agreed standard with the Environment Agency whereby all elements will have sufficient capacity for the estimated 1 in 100 years return period (1% annual probability) flood flow including an allowance for climate change, siltation and blockage. Since the Proposed Scheme will not obstruct any interaction between the mill stream and the natural channel downstream of the route there will be no significant alterations to floodplain mechanics other than design elements such as culverts which are integral to the Proposed Scheme.

4.1.7 Baseline modelling was based solely upon information which was available at the time of this assessment. Due to partially limited land access a number of key structural dimensions within the model were measured by hand or estimated rather than measured using topographic survey instruments.

5 Assumptions and Limitations

5.1 General

5.1.1 This section of the report lists the key assumptions and limitations of the hydrological calculations and hydraulic modelling carried out for this study.

5.2 Hydrology

5.2.1 Flow estimation follows the guidance within the FEH in conjunction with the latest guidance on its use provided by the Environment Agency.

5.2.2 Catchment descriptors have been extracted from the FEH CD ROM (v3) and verified through comparison with OS and LiDAR data where available. Where catchments have been derived by subtracting catchments the area- weighted average method has been used following guidance from volume 5 of the FEH.

5.2.3 ReFH flows have been calculated throughout and validation or calibration of the calculated flows with gauged records has not been carried out due to a lack of available information.

5.3 Use of existing models

5.3.1 An existing model does not exist for this section of the Stoke Book. No existing modelling has therefore been used.

5.4 Hydraulic modelling

5.4.1 Only the assessment of flood risk from the Stoke Brook and the relevant tributaries within the study area has been presented in this report.

5.4.2 All channel and floodplain definitions were created based on the LiDAR ground model. The majority of the floodplain is open and LiDAR quality is therefore expect to be good, however, along the banks of the watercourses there are more dense trees and shrubs and the quality of the filtered LiDAR is therefore lower.

5.5 Topography

5.5.1 No channel is cut within the ground model and therefore the in-channel level represented is actually the water level picked up by the flown LiDAR. No modifications have been made to the ground model to reduce this level to account for in-channel capacity.

5.6 Model parameters

5.6.1 Infiltration losses have not been applied.

5.6.2 Roughness coefficients within the model have been defined using Manning's 'n' values estimated based on site observations. Structural coefficients were estimated based on site observations and measurements where possible.

5.6.3 The upstream and downstream model extents have been located a sufficient distance from the areas of specific interest to ensure stability and accuracy throughout the relevant sections of the model.

5.6.4 Hydrological inflows have generally been applied in the model as point inflows.

5.7 Structures

5.7.1 No topographic survey information was available for the structures within the study area. A general walkover survey was undertaken where access was available, however, given limited or refused access the ability to measure or examine structures was limited.

5.8 Post processing of results

5.8.1 Minor post-processing of results was undertaken to remove blocked areas of floodplain and small dry islands (a tolerance of $10m^2$) was used. Blocked floodplain areas were checked against the one-dimensional model prior to removal to ensure there were no significant errors in conveyance calculation due to inclusion of blocked areas.

5.9 Validation

5.9.1 Sensitivity testing of the model in relation to the downstream boundary and Manning's roughness coefficients has been undertaken and reviewed to improve confidence in the model outputs.

6 References

Institute of Hydrology (1999), *Flood Estimation Handbook.*

Kjeldsen, Jones, Bayliss (2008), *Improving the FEH statistical procedures for flood frequency estimation*. EA/DEFRA report SC050050

Ven Te Chow (1959, 2009 edition), *Open-channel hydraulics.* The Blackburn Press, Caldwell, NJ, USA.